REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
19-04-2016	Final Report	1-Oct-2011 - 31-Oct-2015

4. TITLE AND SUBTITLE
Final Report: Microbiorobots for Manipulation and Sensing

5a. CONTRACT NUMBER
W911NF-11-1-0490

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS
MINJUN KIM, CYNTHIA COLLINS, AGUNG JULIUS

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Drexel University
Office of Research
3201 Arch Street, Suite 100
Philadelphia, PA 19104 -2875

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
59634-NS.25

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
Although nano- and microfabrication techniques are rapidly advancing, it remains a challenge to fabricate separate individual microscale actuators and sensors en masse. A possible resource for such tiny elements exists within microorganisms. Specifically, the abilities of bacteria to move in a self-propelled manner and to detect and process sensory information represent enormous potential that can be harnessed and integrated into microscale robotics and biosensor systems. The objective of the proposed program is to develop a platform that integrates bacteria with

15. SUBJECT TERMS
Microbiorobots, Bacteria, Manipulation, Sensing

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Minjun Kim
					19b. TELEPHONE NUMBER
					215-895-2295

Report Title

Final Report: Microbiorobots for Manipulation and Sensing

ABSTRACT

Although nano- and microfabrication techniques are rapidly advancing, it remains a challenge to fabricate separate individual microscale actuators and sensors en masse. A possible resource for such tiny elements exists within microorganisms. Specifically, the abilities of bacteria to move in a self-propelled manner and to detect and process sensory information represent enormous potential that can be harnessed and integrated into microscale robotics and biosensor systems. The objective of the proposed program is to develop a platform that integrates bacteria with enhanced motility and signaling behavior (through synthetic biology) into a microscale sensing and robotic system. The platform, termed microbiorobots (MBRs), consists of controllable, reconfigurable elements of a microscale sensing and transportation network in biofactory-on-a-chip systems. The goal of this collaborative proposal, initiated at Drexel University with the participation of Rensselaer Polytechnic Institute, is to use multiple types of bacteria, which can be roughly categorized into two functional types, propulsion/actuation and sensing/computation, to enhance the capabilities of existing microrobots through localized sensing and computation. In pursuit of this goal, we use synthetic biology to engineer microbes capable of sensing chemicals or other environmental cues and tuning their motility. In addition we use intercellular communication to further coordinate the microbial populations. The use of bacteria as bio-info-micro systems represents a critical step toward both how microbiorobotics can be introduced as a tool in nano/microscale engineering work as well as how scientists and engineers can learn from nature using modern fabrication, genetic manipulation, and deterministic and stochastic modeling and control. This platform will be applicable in microscale assembly systems and biosensors that require autonomous coordination of bacteria.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
04/19/2016	23.00	Hoyeon Kim, MinJun Kim. Electric field control of bacteria-powered microrobots (BPMs) using static obstacle avoidance algorithm, IEEE TRANSACTIONS ON Robotics, (02 2016): 125. doi:
08/27/2013	4.00	Min Jun Kim, Anak Agung Julius, Dal Hyung Kim, Paul Kim, Yan Ou. Motion control of magnetizedTetrahymena pyriformis cells by amagnetic field with Model PredictiveControl, International Journal of Robotics Research, (01 2013): 129. doi:
10/08/2015	16.00	Aaron Becker, Yan Ou, Anak Agung Julius, Min Jun Kim, Paul Seung Soo Kim. Imparting magnetic dipole heterogeneity to internalized iron oxide nanoparticles for microorganism swarm control, Journal of Nanoparticle Research, (03 2015): 0. doi: 10.1007/s11051-014-2746-y
10/08/2015	17.00	U. Kei Cheang, Min Jun Kim. Self-assembly of robotic micro- and nanoswimmers using magnetic nanoparticles, Journal of Nanoparticle Research, (03 2015): 0. doi: 10.1007/s11051-014-2737-z
10/08/2015	18.00	Hoyeon Kim, Jamel Ali, Kiran Phuyal, Sungsu Park, Min Jun Kim. Investigation of bacterial chemotaxis using a simple three-point microfluidic system, BioChip Journal, (03 2015): 0. doi: 10.1007/s13206-014-9107-x
10/08/2015	19.00	U Kei Cheang, Farshad Meshkati, Dalhyung Kim, Min Jun Kim, Henry Chien Fu. Minimal geometric requirements for micropropulsion via magnetic rotation, Physical Review E, (09 2014): 0. doi: 10.1103/PhysRevE.90.033007
10/08/2015	15.00	Hoyeon Kim, U Kei Cheang, Dalhyung Kim, Jamel Ali, Min Jun Kim. Hydrodynamics of a self-actuated bacterial carpet using microscale particle image velocimetry, Biomicrofluidics, (03 2015): 0. doi: 10.1063/1.4918978
10/08/2015	14.00	U Kei Cheang, Kyoungwoo Lee, Anak Agung Julius, Min Jun Kim. Multiple-robot drug delivery strategy through coordinated teams of microswimmers, Applied Physics Letters, (08 2014): 0. doi: 10.1063/1.4893695

TOTAL: **8**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received		Paper
08/27/2013	3.00	Kiran Phuyal, MinJun Kim. Mechanics of swimming of multi-body bacterial swarmers using nonlabeledcell tracking algorithm, Physics of Fluids, (01 2013): 11901. doi:
TOTAL:		**1**

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper
TOTAL:	

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
08/27/2013	5.00	Yan Ou, Paul Kim, Min Jun Kim, Anak Agung Julius, Aaron Becker. Feedback Control of Many MagnetizedTetrahymena pyriformis Cells by Exploiting Phase Inhomogeneity, IEEE/RSJ International Conference on Intelligent Robots and Systems. 03-NOV-13, . : ,
09/15/2014	10.00	Paul Kim, Aaron Becker, Yan Ou, Agung Julius, Min Jun Kim. Swarm control of cell-based microrobots using a single global magnetic field, International Conference on Ubiquitous Robots and Ambient Intelligence. 30-OCT-13, . : ,
09/15/2014	11.00	Hoyeon Kim, U Kei Cheang, Kyoungwoo Lee, Min Jun Kim. Obstacle Avoidance Method for MicroBioRobots Using Electric Field Control, the 4th Annual IEEE International Conference on CYBER Technology in Automation, Control, and Intelligent Systems (IEEE-CYBER 2014). 04-JUN-14, . : ,
09/15/2014	9.00	Aaron Becker, Yan Ou, Paul Kim, Min Jun Kim, Agung Julius. Feedback control of many magnetized Tetrahymena pyriformis cells by exploiting phase inhomogeneity, IEEE/RSJ International Conference on Intelligent Robots and Systems. 03-NOV-13, . : ,
10/08/2015	22.00	U Kei Cheang, Dejan Milutinovic, Jongeun Choi, Min Jun Kim. TOWARDS MODEL-BASED CONTROL OF ACHIRAL MICROSWIMMERS, the ASME 2014 Dynamic Systems and Control Conference. 22-OCT-14, . : ,
10/08/2015	21.00	Hoyeon Kim, U Kei Cheang, Anak Agung Julius, Min Jun Kim. Dynamic Obstacle Avoidance for Bacteria-Powered Microrobots, IEEE/RSJ International Conferenceon Intelligent Robots and Systems. 28-SEP-15, . : ,
10/08/2015	20.00	Yan Ou, Peter Kang, Min Jun Kim, Anak Agung Julius. Algorithms for Simultaneous Motion Control of Multiple T. PyriformisCells: Model Predictive Control and Particle Swarm Optimization, IEEE International Conference of Robotics and Automation . 26-MAY-15, . : ,

TOTAL: **7**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
08/29/2012	2.00	MINJUN KIM, KIRAN PHUYAL. Mechanics of Swimming of Multi-body Bacterial Swarmers Using Non-Labeled Cell Tracking Algorithm, Physics of Fluids (05 2012)
09/15/2014	8.00	Kyoungwoo Lee, Anak Agung Julius, Min Jun Kim, U Kei Cheang. Multiple-robot drug delivery strategy through coordinated teamsof microswimmers, APPLIED PHYSICS REVIEWS (08 2014)
09/15/2014	7.00	Dal Hyung Kim, , Paul Seung Soo Kim, Kyoungwoo Lee, JinSeok Kim, Min Jun Kim. Galvanotactic behavior of Tetrahymenapyriformisunder electric fields, Journal of Micromechanics & Microengineering (08 2013)

TOTAL: **3**

Number of Manuscripts:

Books

Received		Book
08/29/2012	1.00	MINJUN KIM, A. AGUNG JULIUS, EDWARD STEAGER. Microbiorobotics: Biologically Inspired Microscale Robotic Systems, London: Elesvier, (05 2012)

TOTAL: **1**

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Prof. Kim has been selected to receive the prestigious 2016 Netexplo Award for his work with micro-swimmer robots. Since 2008, based on a panel vote participated in by over 200 experts and business professionals from around the world, UNESCO and Netexplo have announced annually the Netexplo 100, a selection of the 100 most promising digital initiatives. From these, the ten most exceptional, innovative and promising projects are selected as award winners and presented at the Netexplo Forum in Paris. From these ten, a final Grand Prix 2016 award is selected.

Netexplo is an independent observatory that studies the impact of digital technology on society and business. Created in 2007 by Martine Bidegain and Thierry Happe in partnership with the French Senate and the French Ministry for the Digital Economy, Netexplo takes a unique approach to understanding digital society. Through its International University Network, the Netexplo Observatory scans the world for the new faces of tech and their inventions. The founding partners, the Senate, the Ministry for the Digital Economy and HEC Paris business school share with Netexplo a commitment to covering every aspect of digital innovation, whether technological, commercial, organizational, social or environmental.

Dr. Kim's research is with tiny swarming robots that have the potential of swimming through a person's arteries to detect and clear blockages or to deliver a drug to a precise area of the body. As an award winner, he presents his work on February 10, 2016 at Paris-Dauphine University, Paris.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
HOYEON KIM	1.00	
KIRAN PHYUAL	0.50	
ADAM G.W. BOWER	0.50	
PAUL SEUNGSOO KIM	1.00	
JAYAMARY DIVYA RAVICHADNI	1.00	
U KEI CHEANG	0.25	
FTE Equivalent:	**4.25**	
Total Number:	**6**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FARAH TENGRA	0.25
FTE Equivalent:	**0.25**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
MINJUN KIM	1.00	
CYNTHIA COLLINS	0.50	
ANAK AGUNG JULIUS	0.50	
FTE Equivalent:	**2.00**	
Total Number:	**3**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
DAMIEN TURCHI	0.25	Mechanical Engineering
LOUIS ROGOWSKI	0.45	Mechanical Engineering
ALEXANDRA DEAL	0.30	Biosciences
FTE Equivalent:	**1.00**	
Total Number:	**3**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 3.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 3.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 2.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 2.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME	
ADAM G.W. BOWER	
Total Number:	**1**

Names of personnel receiving PHDs

NAME	
PAUL SEUNGSOO KIM	
HOYEON KIM	
Total Number:	**2**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

We have successfully developed a platform that integrates bacteria with enhanced motility and signaling behavior into a microscale sensing and robotic system. The platform, termed microbiorobots (MBRs), consists of controllable, reconfigurable elements of a microscale sensing and transportation network in biofactory-on-a-chip systems. Physically, our MBRs are fabricated microscale chips with bacterial cells attached to their surface. The MBRs are made of materials with neutral buoyancy, thus enabling us to suspend them in a fluidic working environment.

1. We use synthetic biology to harness and improve not only the motility behavior of the bacteria, but also their sensory, biochemical signaling, and information processing capabilities.
2. By integrating these capabilities with the motility behavior of the bacteria, we can achieve autonomous coordination of the microbiorobots, without external signaling mechanisms. Therefore, our proposed system is controllable in the conventional way (i.e. by using external signaling), as well as through local, internal signaling or autonomous coordination.

We have used multiple types of bacteria that can be roughly categorized into two functional types, propulsion/actuation and sensing/computation. In pursuit of this goal, we have developed synthetic biology to engineer microbes capable of sensing chemicals or other environmental cues and tuning their motility. In addition, we have used intercellular communication to further coordinate the microbial populations. The use of synthetic biology allows us to build systems that can be easily tuned and manipulated, providing an experimental system where we have the unique ability to adjust a variety of parameters. The propulsion/actuation functionality is provided by swimming, flagellated bacteria that deliver propulsive forces for the MBRs. The sensing/computation functionality is provided by genetically engineering bacteria cells that contain novel synthetic genetic networks that enable them to sense and produce various types of small signal molecules. These small signal molecules are used as tokens of information that can be processed with appropriate synthetic networks. The sensing and computation capabilities of the bacteria have been used in autonomous coordination of the MBRs and in their utilization as biosensors.

Fundamental scientific progresses addressed by this research program include (i) the use of synthetic biology in hybrid microrobotics, (ii) obtaining answers to basic questions regarding methods for control input generation using external stimuli that lead to vision-based feedback control of MBRs, (iii) the possibility of using cell-cell communication for coordinated, population level behaviors to achieve biosensing and swarm control of MBRs, thus enabling an entirely new class of sensing and actuation systems. The ability to complete this all at the microscale enables the realization of miniaturized biofactories whose applications are limited only by our imagination but include in vitro procision drug delivery and chemical sensors, each of which has its own needs. Given the still embryonic state of microbiorobotics, any significant progress toward the control of genetically modified engineered bacteria has great impact.

Technology Transfer

N/A

Autonomous Motion Control of Bacteria Powered Microrobots Using Electric Fields

Ph.D Thesis Defense

April 1th, 2016

Hoyeon Kim

Advisor : Prof. Min Jun Kim

Biological Actuation, Sensing & Transport Laboratory
Mechanical Engineering and Mechanics
Drexel University

CONTENTS

I. Introduction
- Motivation
- Reviews
- Objective

II. Research works
- Hydrodynamics of Bacterial carpet using μPIV
- Static Obstacle Avoidance for Bacteria Powered Microrobots
- Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

V. Achievements

CONTENTS

I. Introduction
- Motivation
- Reviews
- Objective

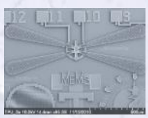
II. Research works
- Hydrodynamics of Bacterial carpet using μPIV
- Static Obstacle Avoidance for Bacteria Powered Microrobots
- Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

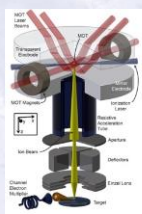
IV. Future Works

V. Achievements

Motivation

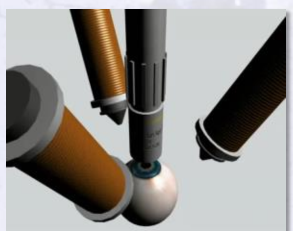


- MEMS



- FIB equipment

- Potential tasks



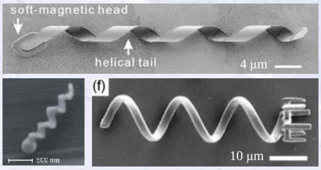
www.youtube.com/watch?v=1R0EHe9iYQw www.youtube.com/watch?v=KqW3LtcQoZY www.youtube.com/watch?v=fXzVNSxWIBg

Motivation

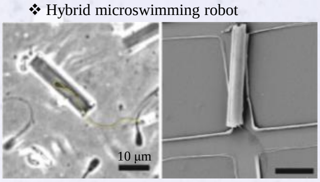
❑ Technologic Issues for Microrobotics

Fabrication

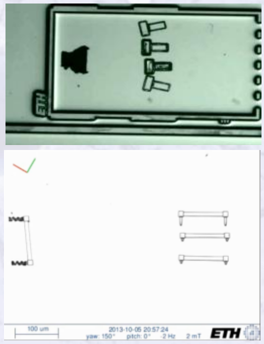
❖ Artificial microswimming robot



❖ Hybrid microswimming robot



Control



Advanced technology

Issues for the advanced task

- ✓Localization
- ✓Navigation
- ✓Motion control for specific tasks

Autonomous navigation

- ✓Support optimal path
- ✓Prevent damage of microrobot
- ✓Save time, energy
- ✓Increase efficiency

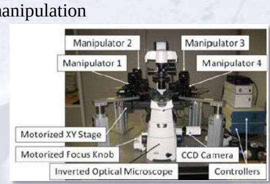
Ghosh 2009 Floyd 2008 Zhang 2009 Ghosh 2009

ETH at 2010 NIST Mobile Microrobotics Challenge, T.Y Hung, 2014,

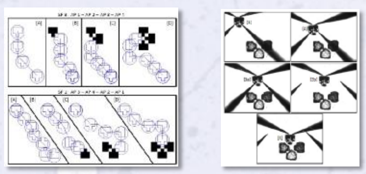
Reviews

❑ Autonomous motion control for navigation

1. Micromanipulation



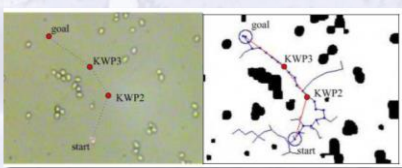
Davide J 2011



- Microassembly test result using A*

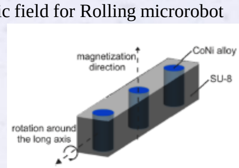
2. Optical Tweezer

Tao J. 2011

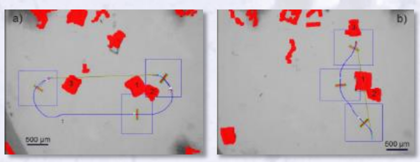


- Cell transportation using RRT

3. Magnetic field for Rolling microrobot



Samuel C. 2015

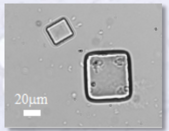


- Motion planning using RRT

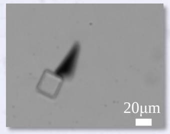
Objectives

- An autonomous navigation algorithm using Bacteria Powered Microrobots

  1. Static obstacle avoidance
  2. Dynamic obstacle avoidance



• Collision with static obstacle



• Collision with dynamic obstacle

- Hydrodynamics of bacterial carpet under boundary effect

  1. Visualize the flow field using μPIV
  2. Analyze the flow field with bounded and unbounded condition

CONTENTS

I. Introduction
- Motivation
- Reviews
- Objective

II. **Research works**
- Hydrodynamics of Bacterial carpet using μPIV
- Static Obstacle Avoidance for Bacteria Powered Microrobots
- Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

V. Achievements

Bacteria Powered Microrobots

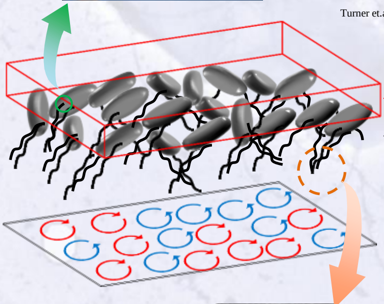
❑ Introduction of Bacteria Powered Microrobots (BPMs)

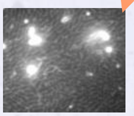
▪ Concept of BPM

• Flagellum motor

• Swimming motion of bacteria

Turner et.al, 2000





Kim 2009

Characteristics of Bacteria in Swimming

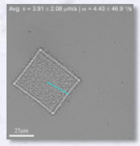
✓ 3D motion in fluids
✓ 3 – 5 peritrichous flagella
✓ Flagella bundle when all motors turn CCW
✓ When motors turn CW, bacteria tumble
✓ Average swimming velocity: 12 – 50 μm/s
✓ Random walk

Inorganic body (SU-8 structure)

Biomolecular actuator of bacterial carpet (*Serratia marcescens*)

• Example of BPM

• Self-actuation of BPM

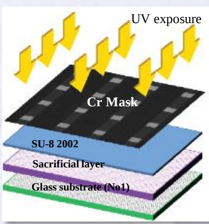


Collective Motion of Flagella

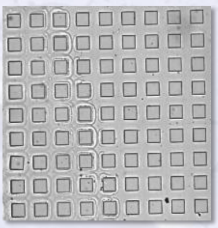
✓ Local fluid flow motion
✓ Large global coordination due to hydrodynamic interaction
✓ A net thrust on the microsturcture causing rotational and/or translational movement

Bacteria Powered Microrobots

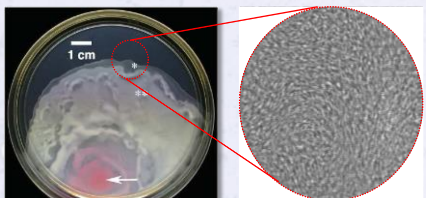
❑ Fabrication of Bacteria Powered Microrobots



• Fabrication of microstructure

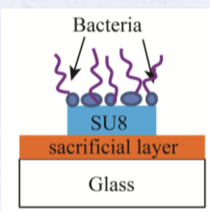


• Release microstructure by Dextran layer

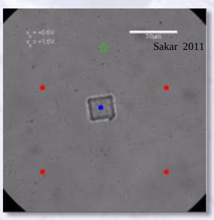


Steager et. al, 2008

• Swarming agar plate (*Serratia marcescens*)



• Scheme of a BPM



• Electrophoretic control

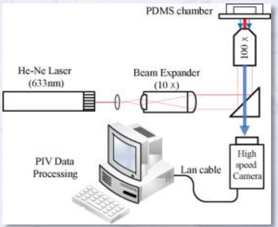
Advantage of biological microrobots

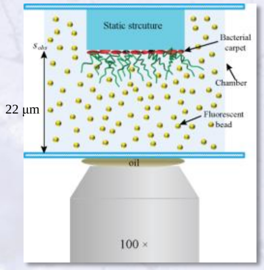
✓ Draw energy from fluid
✓ Easily manufactured
✓ Self-coordinated (quorum sensing or hydrodynamics)
✓ Fully controllable due to negative charge in body
✓ Adjust orientation of microrobots

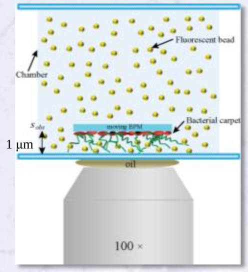
I Hydrodynamics of Bacterial carpet

❑ Propulsive force by bacterial carpet

1. System setup

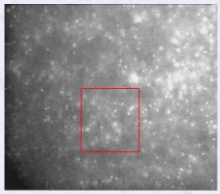


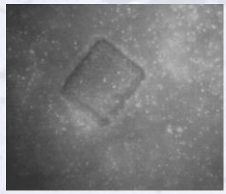




- Tethered structure
- Untethered structure(Self-actuation of BPM)

- µPIV setup
  - Laser : 633 nm He-Ne laser
  - Fluorescent bead size : 0.2µm diameter
  - Camera : High speed camera 250 fps
  - Objective lens : 100 ×
- Tethered structure
  - Dimension : 32 × 34 µm^2
  - Thickness : 35 µm using SU-8 2035
- Untethered structure (BPM)
  - Dimension : 32 × 34 µm^2
  - Thickness : 3 µm using SU-8 2002
- Observed planes
  - Untethered case : 12 planes (0~22 µm)
  - Tethered case : 1 plane (1 µm)



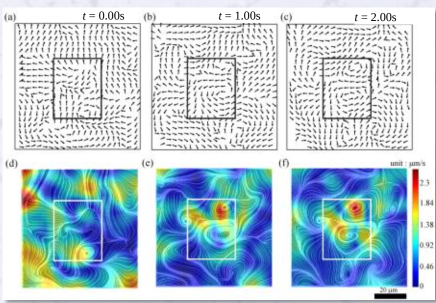


- Tethered case
- Untethered case

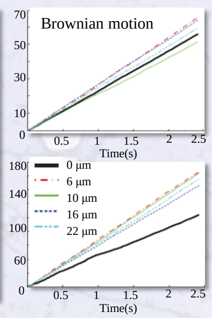
I Hydrodynamics of Bacterial carpet

❑ Propulsive force by bacterial carpet

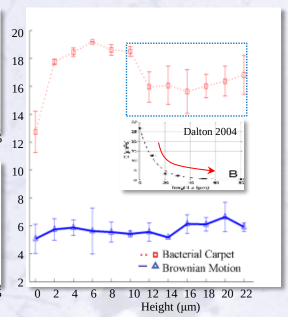
2. Experimental results : Tethered structure cases



- Flow field tethered structure (at 6 µm height from bacterial carpet)



- MSD (µm^2) comparison



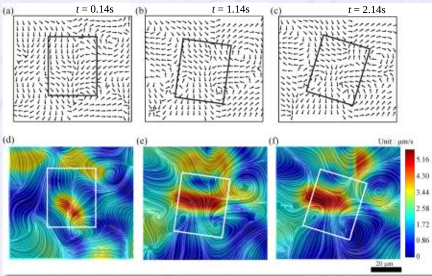
- Diffusion coefficient comparison

- Results summary
  - There are variance on Brownian motion due to measurement noise.
  - The bacterial carpet generates much stronger flow field than Brownian motion.
  - The strongest flow is generated at 6~8 µm height from the bacterial carpet.
  - The flow field is not decreasing dramatically like 'Dalton paper'.
  - The bounded condition (less than 80 µm distance with boundary) affect the flow fields on more than 12 µm height.

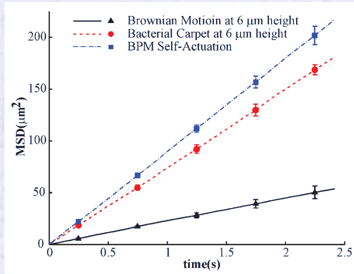
I Hydrodynamics of Bacterial carpet

❑ Propulsive force by bacterial carpet

3. Experimental results : Untethered structure cases



- Untethered structure(Self-actuation of BPM)



- MSD comparison

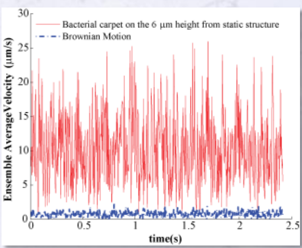
▪ Results summary

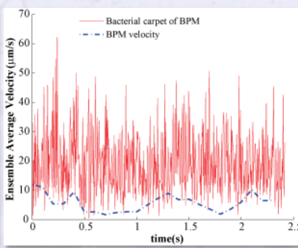
- ➢ The bacterial carpet was close to wall and boundary effects on the flagella-induced flow field must be taken into account.
- ➢ The bacteria secreted lubrication layer, a thin layer of liquid, approximately 1 μm in depth, separates the bacterial carpet from the glass substrate.
- ➢ The strong velocity flow profile was observed above the middle of the moving BPM.
- ➢ The strong streams of flow were much stronger in the moving BPM than the same area on the static structure surface.
- ➢ The MSD of the untethered BPM is larger than the tethered cases by 36.3 μm^2.

I Hydrodynamics of Bacterial carpet

❑ Propulsive force by bacterial carpet

4. Comparison of ensemble velocity



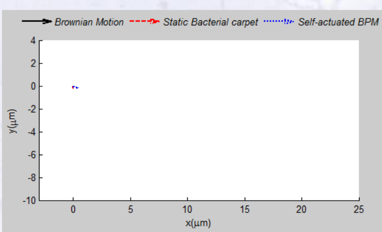


- Ensemble Average Velocity

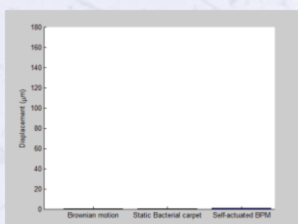
	Average	std
Tethered	10.2 μm/s	5.3
Untethered	20 μm/s	10.4

▪ Results summary

- ➢ The effect of the fluid near-boundary leads to the increase of the resistance coefficients in terms of normal and longitudinal resistance.



- Ensemble motion



- Accumulation of displacement

CONTENTS

I. Introduction
- Motivation
- Reviews
- Objective

II. Research works
- Hydrodynamics of Bacterial carpet using μPIV
- Static Obstacle Avoidance for Bacteria Powered Microrobots
- Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

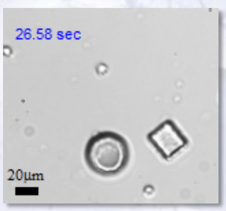
V. Achievements

II Static Obstacle Avoidance

❑ Constraint elements for obstacle avoidance using BPMs

1. Self-actuation of BMPs

- Uncontrollable motion

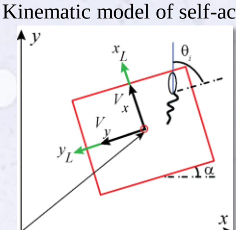


- Collision with obstacle

High probability of collision risk

- ✓ Inherent motion of BPMs caused by bacterial carpets
- ✓ Uncontrollable motion by electric fields
- ✓ The resultant locomotion by self-actuation and electrophoretic motion

- Kinematic model of self-actuation BMP



- Coordinate system

- Self-actuation velocities

$$\boxed{V_x = \bar{p}\boldsymbol{\beta}_1 , V_y = \bar{p}\boldsymbol{\beta}_2, \alpha = \bar{p}\boldsymbol{\beta}_3}$$

$$\boldsymbol{\beta}_1 := \left(\frac{1}{k_t}\right)\sum_{i=1}^{N_b} cos\theta_i \qquad \boldsymbol{\beta}_2 := \left(\frac{1}{k_t}\right)\sum_{i=1}^{N_b} sin\theta_i$$

$$\boldsymbol{\beta}_3 := \left(\frac{1}{k_r}\right)\sum_{i=1}^{N_b} (b_{i_x} sin\theta_i - b_{i,y} cos\theta_i)$$

II Static Obstacle Avoidance

❑ Constraint elements for obstacle avoidance using BPMs

1. Self-actuation of BMPs

- Global coordinate system for position of BPMs

$$V_{gx} = V_x cos\theta - V_y sin\theta$$
$$V_{gy} = V_x sin\theta + V_y cos\theta$$

$$\Delta d_x = \boldsymbol{\beta_4} U_x$$
$$\Delta d_y = \boldsymbol{\beta_4} U_y$$

where, $V_x = \bar{p}\boldsymbol{\beta_1}$, $V_y = \bar{p}\boldsymbol{\beta_2}$, $\alpha = \bar{p}\boldsymbol{\beta_3}$, $\boldsymbol{\beta_4}$: *Electrophoretic property*

$\bar{p}$: mean propulsive force (0.41pN).

- Kinematic model of BMP's locomotion

$$p_i = p_{i-1} + Locomotion_{\boldsymbol{self-actuation}} + Locomotion_{\boldsymbol{electrokinetic}}$$

$$\begin{pmatrix} x_i \\ y_i \\ \theta_i \end{pmatrix} = \begin{pmatrix} x_{i-1} \\ y_{i-1} \\ \theta_{i-1} \end{pmatrix} + \bar{p}\begin{bmatrix} cos\theta_{i-1} & -sin\theta_{i-1} & 0 \\ sin\theta_{i-1} & cos\theta_{i-1} & 0 \\ 0 & 0 & \alpha \end{bmatrix}\begin{bmatrix} \boldsymbol{\beta_1} \\ \boldsymbol{\beta_2} \\ \boldsymbol{\beta_3} \end{bmatrix} t_s + \begin{pmatrix} U_x \\ U_y \\ 0 \end{pmatrix} \boldsymbol{\beta_4} t_s$$

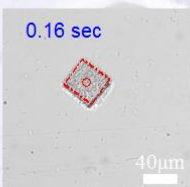
Unit : $\beta_1, \beta_2: \frac{\mu m}{spN}$, $\beta_3: \frac{rad}{spN}$, $\beta_4: \frac{\mu m}{sVcm}$

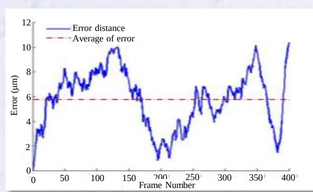
II Static Obstacle Avoidance

❑ Constraint elements for obstacle avoidance using BPMs

2. Reliability of kinematic model

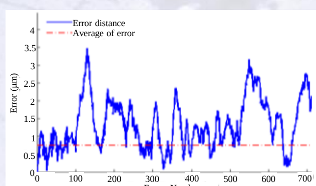
- Modeling Validation using 40 × 43 μm^2





- Self-actuation
- Motion with +20 V/cm (right direction)

- Modeling Validation using 20 × 23 μm^2



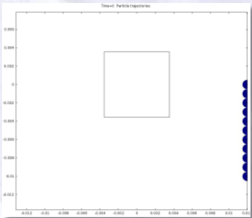
II Static Obstacle Avoidance

❑ Constraint elements for obstacle avoidance using BPMs

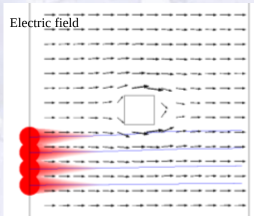
3. Distorted electric field around obstacles

- Unmatched movement with desired motion
  - ○ COMSOL Simulation Setup : Particle is negative charged particle. (9.1×10^{-17} kg, -1.6021×10^{11} C),
    Obstacle is regarded as insulator, Input - Anode (Left), Cathode (Right) with 10 V/cm

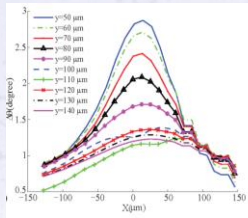
• Particle motion



• Result of Particle trajectories



• The difference of heading angle

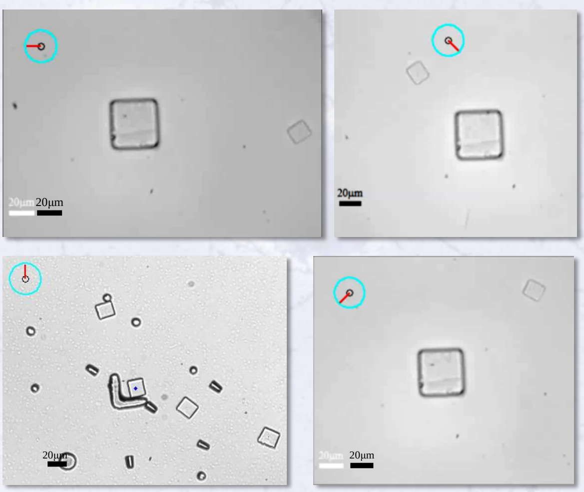


- Simulation Summary
  - ✓ There exist zero potential area around the obstacle which gives non-mobility to the particle.
  - ✓ The deformed electric field steers the particle toward the distorted angle. (Maximum 3º)
  - ✓ As far away from obstacles, the effect of distorted electric field becomes week.

II Static Obstacle Avoidance

❑ Constraint elements for obstacle avoidance using BPMs

4. The effect of distorted electric field



: Electric field direction

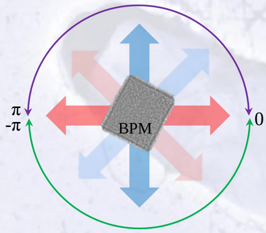
- Demonstration Result
  - ✓ BPM cannot move at zero potential area.
  - ✓ BPM follows the deformed electric field.

II Static Obstacle Avoidance

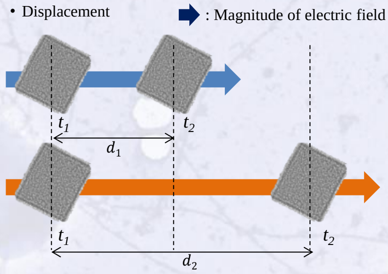
❑ Constraint elements for obstacle avoidance using BPMs

5. Omnidirectional motion (holonomic motion)

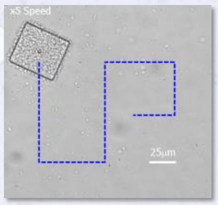
• Direction of electric field



• Displacement



• Motion example



Kim Group 2007

▪ Control characteristics

✓ The direction of electric field results from *x* voltage, *y* voltage inputs.

✓ The magnitude of electric field is proportional to the sum of *x* voltage, *y* voltage inputs.

✓ The superposed electric field can be a range of 0~360º.

✓ The maximum resultant control input is 20 V/cm in the system.

II Static Obstacle Avoidance

❑ Proposed Static Obstacle Avoidance Approach

1. Obstacle avoidance approach based on an objective function

$$f(U_x, U_y) = \alpha\ heading(U_x, U_y, Goal) + \gamma\ movement(U_x, U_y) + \omega\ clearance(U_x, U_y) + \delta\ control(U_x, U_y)$$

1) heading( ) : to choose the input which makes BPM head to the goal

2) movement( ) : to choose the input which makes BPM move a longer displacement

3) clearance( ) : to avoid the input which makes BPM collide to obstacles

4) control( ) : to choose the input which makes BPM move toward strong controllable area

▪ The procedure to choose the control input from the objective function

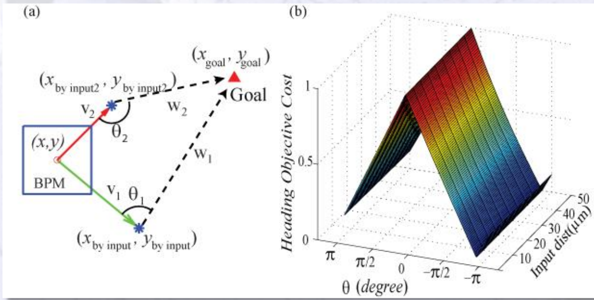
1. Consider the instant position of a BPM with boundary information
2. Calculate each function of the objective function depending on all admissible control inputs
3. Find an optimal control input which has the maximum cost of the objective function

II Static Obstacle Avoidance

❑ Proposed Static Obstacle Avoidance Approach

2. *heading* function

$$heading(U_x, U_y, Goal) = \frac{v \cdot w}{|v||w|} \div \pi$$



- Situation of a BPM and Goal
- Resultant cost

3. *movement* function

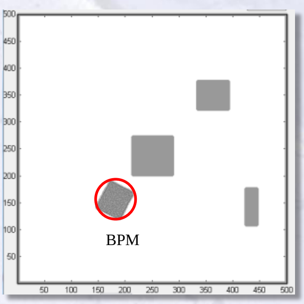
$$movement(U_x, U_y) = \beta_4 t_s \sqrt{U_x{}^2 + U_y{}^2}$$

II Static Obstacle Avoidance

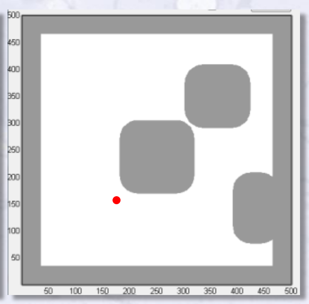
❑ Proposed Static Obstacle Avoidance Approach

4. *clearance* function

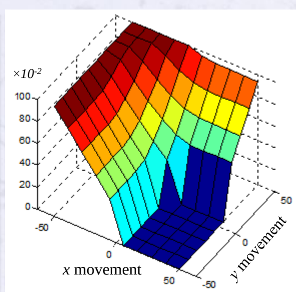
$$clearance(U_x, U_y) \propto \frac{1}{dist(cspace)}$$



- Map (500 μm x500 μm)



- *C*-space to check collision



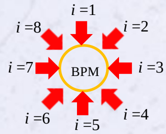
- Resultant cost

II Static Obstacle Avoidance

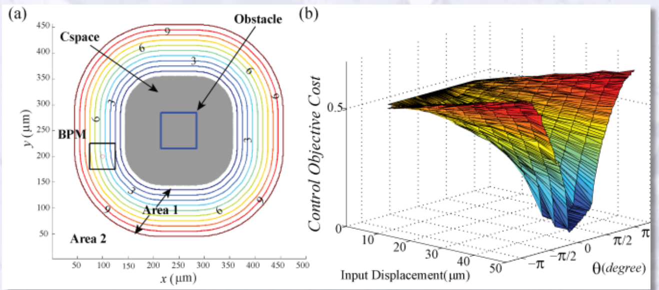
❑ Proposed Static Obstacle Avoidance Approach

5. *control* function

$$control(U_x, U_y) = \sum_{i=1}^{8} \frac{\overleftrightarrow{EF} \cdot \overrightarrow{Input(U_{xi}, U_{yi})}}{|\overleftrightarrow{EF}|}$$



• At the next position



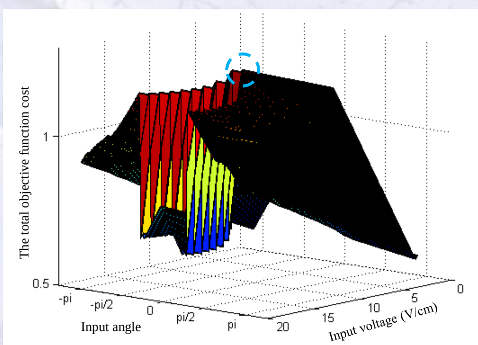
• Intrinsic potential field • Resultant cost

II Static Obstacle Avoidance

❑ Proposed Static Obstacle Avoidance Approach

6. The chosen input from total value of the objective function

$$f(U_x, U_y) = \boldsymbol{\alpha}\ heading(U_x, U_y, Goal) + \boldsymbol{\gamma}\ movement(U_x, U_y) + \boldsymbol{\omega}\ clearance(U_x, U_y) + \boldsymbol{\delta}\ control(U_x, U_y)$$



• Result of the objective function

- Characteristic of the objective function

✓ Optimal input to maximize the cost of objective function depending on weight values of α, γ, ω, δ.

II Static Obstacle Avoidance

❑ Experimental Results

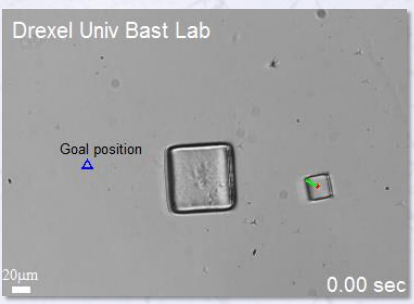
1. System setup

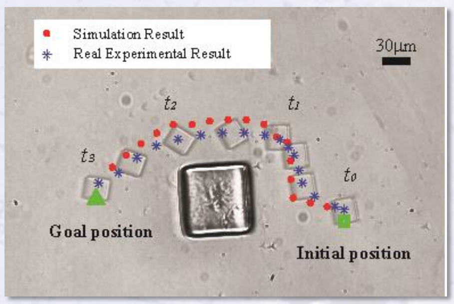
- Obstacle structures
  - Material : SU-8 2010
  - Height : 20 μm
- BPMs
  - Material : SU-8 2002
  - Shape : 32 × 30 μm^2
  - Height : 3 μm
- Control System
  - 0.16 sampling time
  - C++ programming
  - GUI interface
- Experiment Chamber
  - Material : PDMS
  - Filled with PBS buffer
  - Two pairs of platinum wire

II Static Obstacle Avoidance

❑ Experimental Results

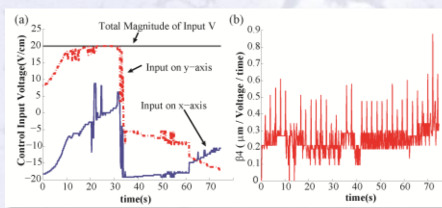
2. Single obstacle avoidance with simulation result





- ➢ One obstacle environment (71 × 74 μm^2)
- ➢ Maximum Voltage input: 20 V/cm
- ➢ Parameters for algorithm

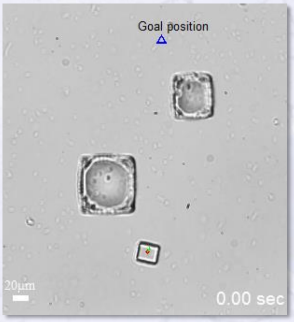
α	γ	ω	δ	β_1	β_2	β_3	β_4
0.25	0.3	0.5	0.5	0.01	0.03	0.01	0.32

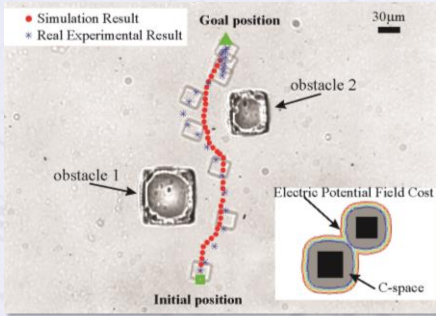


II Static Obstacle Avoidance

❑ Experimental Results

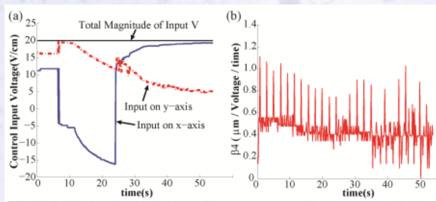
3. Two obstacles avoidance with simulation result





- Two obstacles environment (71×74 μm^2 and 52×57 μm^2)
- Maximum Voltage input: 20 V/cm
- Parameters for algorithm

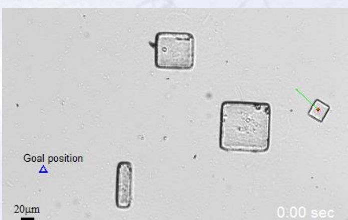
α	γ	ω	δ	β_1	β_2	β_3	β_4
0.5	0.4	0.8	0.41	0.1	0.02	0.01	0.14

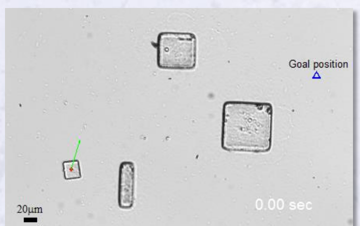


II Static Obstacle Avoidance

❑ Experimental Results

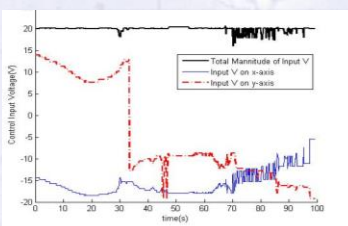
4. Routing motion with different weight values

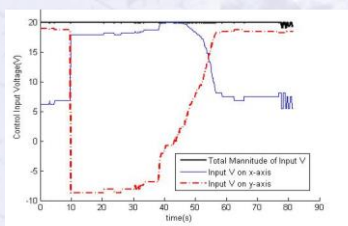




$(heading: 0.4, movement: 0.3, clearance: 0.6, control: 0.55)$

$(heading: 0.45, movement: 0.3, clearance: 0.6, control: 0.7)$





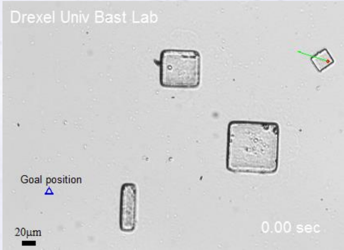
• Control input

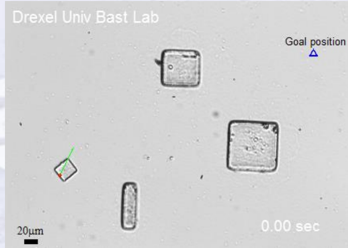
• Control input

II Static Obstacle Avoidance

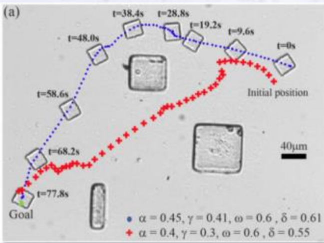
❑ Experimental Results

5. Routing motion with different weight values II

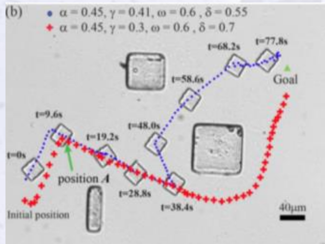




$(heading : 0.45\ movement : 0.41, clearance: 0.6, control : 0.61)$ $(heading : 0.45, movement: 0.41, clearance: 0.6, control : 0.55)$



• Comparison of trajectories

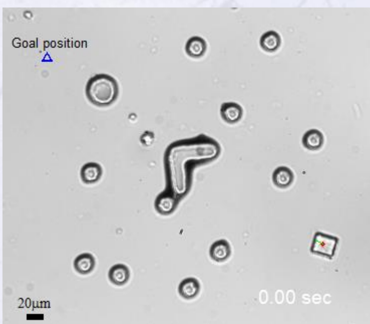


• Comparison of trajectories

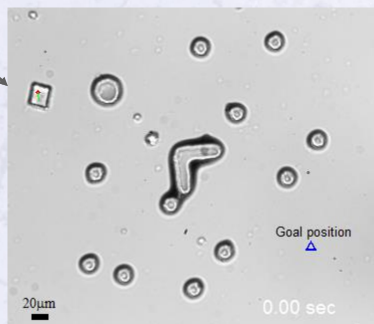
II Static Obstacle Avoidance

❑ Experimental Results

6. Routing motion in Multiple obstacles with different weight values

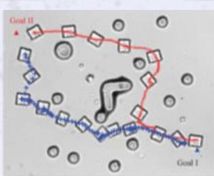


Return
to
the initial position



α = 0.8, γ = 0.5, ω = 0.54 ,δ = 0.5

α = 0.8, γ = 0.5, ω = 0.44 ,δ = 0.5

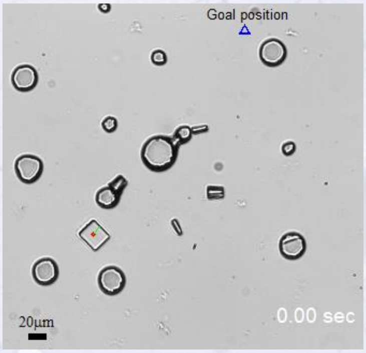


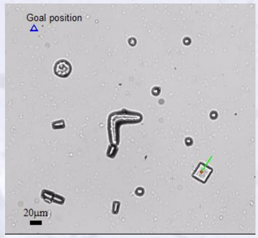
• Comparison of trajectories

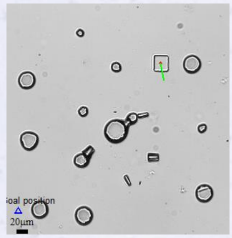
II Static Obstacle Avoidance

❑ Experimental Results

7. Other Multiple obstacles avoidance results







	Min *d* between obstacles	Total Exp. No	Success rate
One obstacle	N/A	3	100%
Two obstacles	60	3	100%
Three obstacles	50	10	100%
Multiple obstacles	30	18	88%

- Summary of experimental results
  - ✓ The feasibility of the algorithm is verified with different conditions and various BPMs.
  - ✓ The trajectories result from the different weighting $\alpha,\gamma,\omega,\delta$.
  - ✓ Most cases have applied BPMs with the maximum control input voltage.

CONTENTS

I. Introduction
- Motivation
- Reviews
- Objective

II. Research works
- Hydrodynamics of Bacterial carpet using μPIV
- Static Obstacle Avoidance for Bacteria Powered Microrobots
- Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

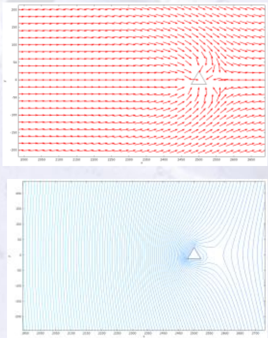
V. Achievements

III Dynamic Obstacle Avoidance

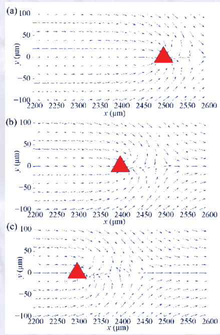
❑ Constraint elements for obstacle avoidance using BPMs

1. Distorted electric field around dynamic obstacles : undesired control result

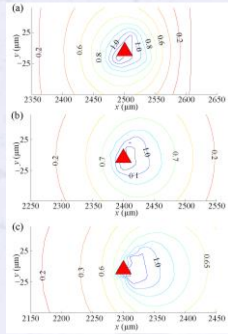
- Undesired control result
  - COMSOL Multiphysics Simulation Setup : Moving mesh, 10 μm/s with –*x*-direction. Electric field with 10 V/cm



• COMSOL simulation results



• Distorted electric field



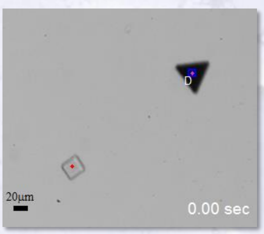
• Profile of Distorted electric field

- Simulation Summary
  - ✓ The distorted electric field area forms a ripple formation from the obstacle.
  - ✓ The back side of the object has more ununiformed electric potential field.

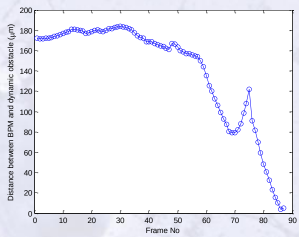
III Dynamic Obstacle Avoidance

❑ Constraint elements for obstacle avoidance using BPMs

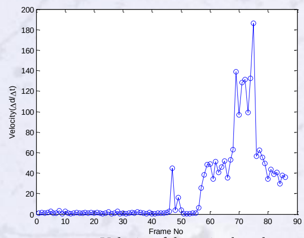
2. Unexpected motion speed of dynamic obstacle



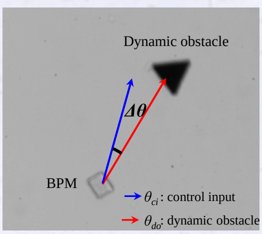
• Demonstrate of collision risk



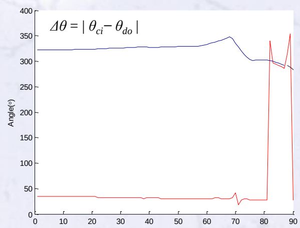
• Distance between BPM and dynamic obstacle



• Velocity of dynamic obstacle



• Description of $\Delta\theta$



• The difference of control input angle

- High probability of collision risk
  - ✓ The high collision risk results from a sudden speed of dynamic obstacle.
  - ✓ The motion of dynamic obstacle will be unpredictable.

III Dynamic Obstacle Avoidance

❑ Proposed Dynamic Obstacle Avoidance Approach

1. Supplementary VFH method to the static obstacle avoidance approach

Procedure to choose the optimal control input

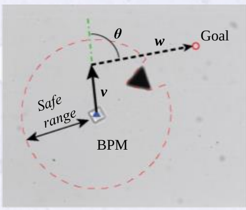
Step 1 : Exclude the control inputs which heads to obstacles using the redefined VFH $(v(U,\theta))$

$\boldsymbol{\theta}_v = \{\theta_i\} \quad for \quad BD(\theta_i) \leq safe\,range, \quad 1 \leq i \leq 360$

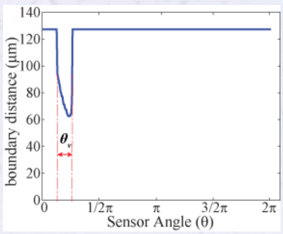
$T_\theta = \min(|\theta - \boldsymbol{\theta}_v|)$

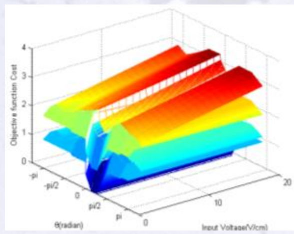
$$v(U,\theta) = \left\{ \begin{matrix} 0 & if\ T_\theta \leq \varepsilon_s \\ \frac{T_\theta^2}{T_{max}^2} & if\ \varepsilon_s < T_\theta \leq T_{max} \\ 1 & if\ T_{max} \leq T_\theta \end{matrix} \right\}$$

Step 2 : Find the optimal control input using objective function on remained candidate inputs



▪ Location of BPM and dynamic obstacle

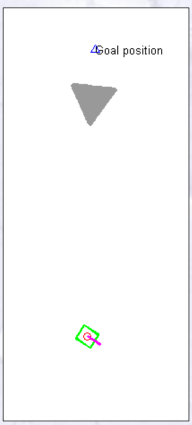


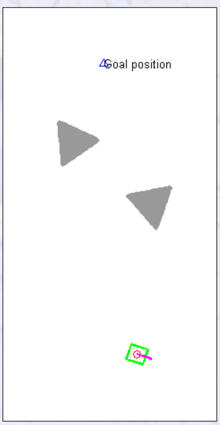


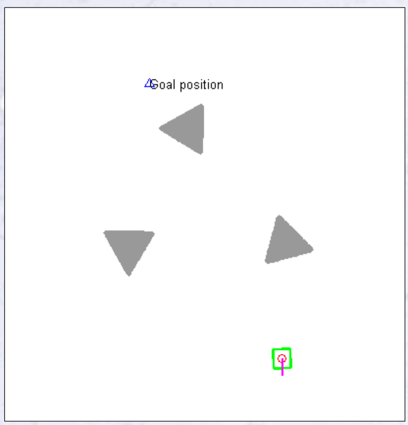
II Dynamic Obstacle Avoidance

❑ Proposed Dynamic Obstacle Avoidance Approach

2. Simulation of the proposed approach using MATLAB







III Dynamic Obstacle Avoidance

❑ Proposed Dynamic Obstacle Avoidance Approach

3. Evaluation of performance in terms of potential risk

Danger Index : $\boldsymbol{g_D(D_{BO}) \cdot g_A(A_{CO})}$

➢ Product method based criterion

1st Factor : The relative distance factor between BPM and dynamic obstacle

D_{BO} : *the distance between the BPM and the obstacle*

$$g_D(D_{BO}) = \left\langle \begin{array}{ccc} 0 & : & D_{BO} \geq D_{max} \\ k\left(\frac{1}{D_{BO}} - \frac{1}{D_m}\right) & : & D_{BO} < D_{max} \end{array} \right\rangle$$

$$where, \;\; k = \frac{D_{max}}{D_{min}}$$

$$D_{max} = \; maximum\ allowable\ distacne\ between\ the\ BPM\ and\ the\ obstacle\ (safe\ range)$$

$$D_{min} = \; Radius_{BPM} * kv + Movement_{self} \;\; , \;\; kv = \frac{V_{mean\ of\ dynamic\ obstalce}}{V_{mean\ of\ BPM}}$$

2nd Factor : The relative angle of control input comparing to the angle toward the dynamic obstacles

A_{CO} : *the angle gap between the control input and the heading angel from BPM to the obstacle*

$$g_A(A_{CO}) = \left\langle \begin{array}{ccc} 0 & : & A_{CO} \geq D_{blockAng}(D_{BO})/2 + \theta_{by\ self-actuation} \\ \frac{A_{CO}}{D_{blockAng}(D_{BO})/2 + \theta_{by\ self-actuation}} & : & A_{CO} < D_{blockAng}(D_{BO})/2 + \theta_{by\ self-actuation} \end{array} \right\rangle$$

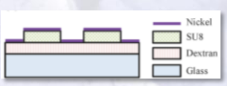
$$where, \;\; D_{blockAng}(D_{BO}) = \; the\ angle\ that\ represents\ occupied\ angle\ by\ obstacle\ depending\ on\ D_{BO}$$

III Dynamic Obstacle Avoidance

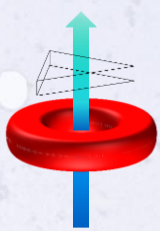
❑ Experimental Results

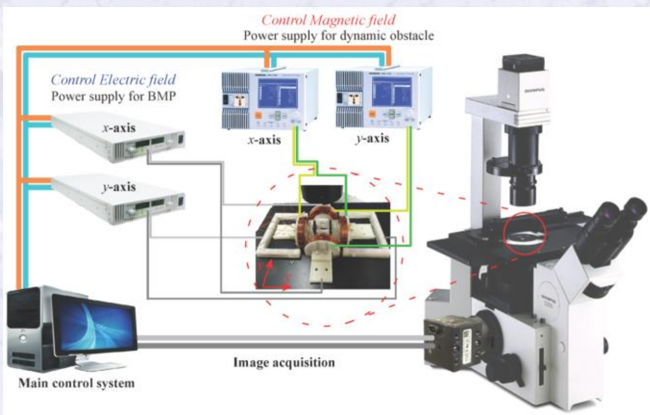
1. System setup

- Dynamic obstacle structures
  - Material : SU-8 2010
  - Thickness : 3 µm
  - Nickel deposition : 200 nm



- *z*-coil to overcome friction
  - Lift force : 1.5mT (2V)
  - Tilt the structure





- Control System for main algorithm
  - 0.16 sampling time
  - C++ programming
  - GUI interface to input goal position
- Control System for dynamic obstacle
  - 0.16 sampling time
  - C++ programming
  - GUI interface for manual control

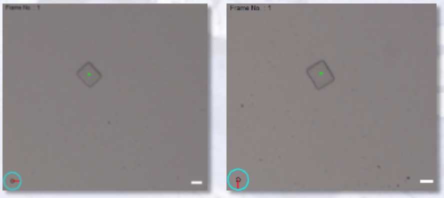
III Dynamic Obstacle Avoidance

❑ Experimental Results

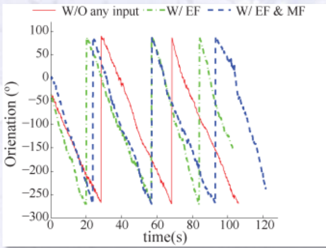
2. Magnetotaxis test on BPMs w/wo electric fields

- Setup : Magnetic field for more than 2 min with 20 Voltage input

1. Self-actuation test



2. Electric field test



- Comparison of orientation angle velocity

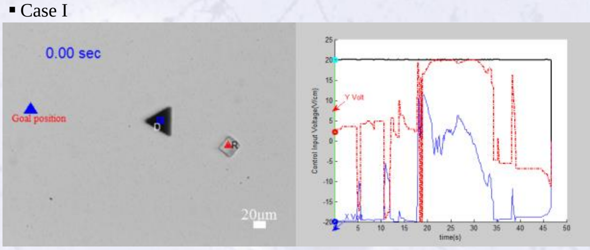
- Magnetotaxis test results
  - ✓ In terms of self-actuation, there is not critical difference with/without magnetic fields..
  - ✓ The motion control of BPMs is not affected by the magnetic fields.
  - ✓ It is not a problem with the application of magnetic fields for dynamic obstacles.

III Dynamic Obstacle Avoidance

❑ Experimental Results

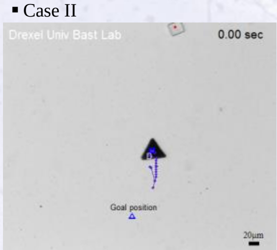
3. Single dynamic obstacle avoidance

- Case I

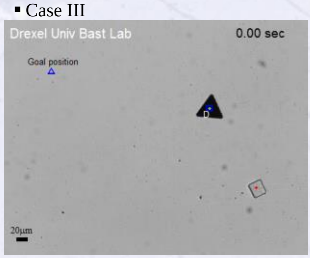


Case	α	γ	ω	δ	*Safe range*
I	0.5	0.6	0.5	0.7	100
II	0.5	0.5	0.7	0.5	80
III	0.3	0.2	0.5	0.7	100
IV	0.3	0.4	0.6	0.5	70

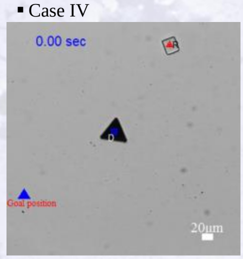
- Case II



- Case III



- Case IV

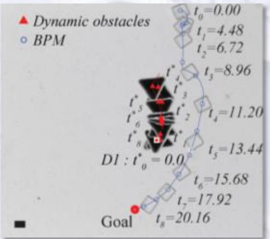


III Dynamic Obstacle Avoidance

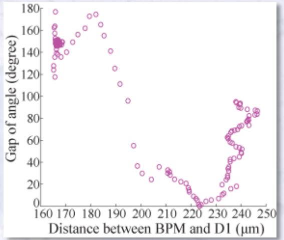
❑ Experimental Results

4. Danger index for single dynamic obstacle avoidance experiments

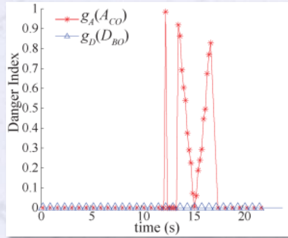
▪ Example using Case II



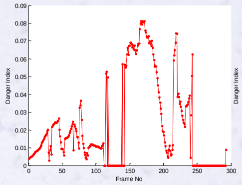
• Resultant trajectories



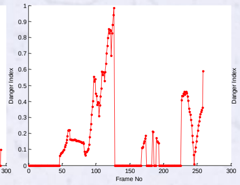
• Relationship between gap and distance



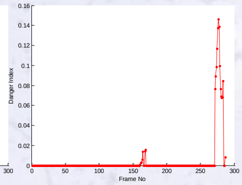
• danger cost using $g_A(A_{co})$ and $g_D(D_{BO})$



• Danger index of Case I



• Danger index of Case III



• Danger index of Case IV

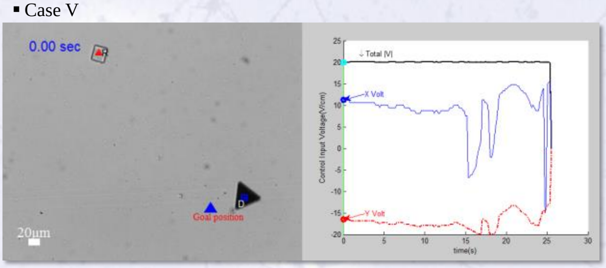
Case	BPM $\bar{v}$	Dynamic obstacle v mean	Dynamic obstacle v max	*Mean distant*
I	9.6	12.0	92.6	40.2
II	18.7	5.3	102.4	30.3
III	15.8	29.1	57.4	29.1
IV	12.0	13.5	85.7	75.0

III Dynamic Obstacle Avoidance

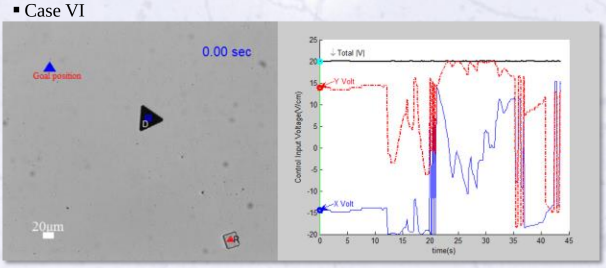
❑ Experimental Results

5. Single dynamic obstacle avoidance using strong self-actuation BPMs

▪ Case V



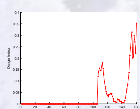
▪ Case VI



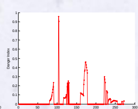
Case	α	γ	ω	δ	*Safe range*
V	0.3	0.2	0.5	0.6	100
VI	0.3	0.2	0.7	0.6	80

Case	β_1	β_2	β_3	β_4	*Mean danger index*
V	-20.3	12.1	6.8	0.8	0.095
VI	-7.6	-12.6	7.1	0.9	0.146

Case	BPM $\bar{v}$	Dynamic obstacle v mean	Dynamic obstacle v max	*Mean distant*
V	20.1	9.7	99.1	40.2
VI	15.3	14.3	99.8	30.3



▪ Danger index of Case V



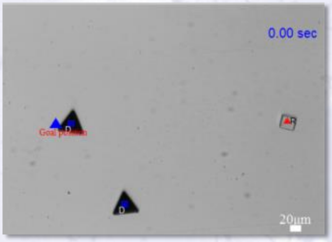
▪ Danger index of Case VI

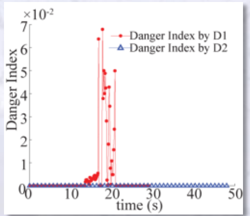
III Dynamic Obstacle Avoidance

❑ Experimental Results

6. Multi dynamic obstacle avoidance

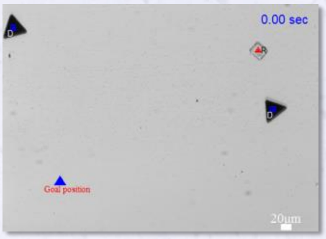
▪ Case VII

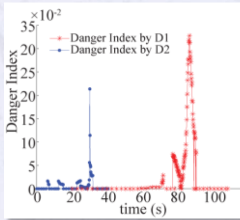




• Danger index of Case VII

▪ Case VIII





• Danger index of Case VIII

Case	α	γ	ω	δ	*Safe range*
VII	0.3	0.4	0.6	0.5	120
VIII	0.3	0.2	0.7	0.5	100

Case	β_1	β_2	β_3	β_4	*Mean danger index*
VII	-1.89	5.03	0.01	0.76	0.15
VIII	5.01	6.20	0.08	0.81	0.02

Case	BPM $\bar{v}$	Dynamic obstacle v			
		mean		max	
VII	10.9	12.7	116.1	10.9	167.7
VIII	15.3	14.3	100.9	21.7	180.9

Summary of experimental results

✓The feasibility of the algorithm is verified with various situations.

✓The performance is evaluated using the danger index.

CONTENTS

I. Introduction
- Motivation
- Reviews
- Objective

II. Research works
- Hydrodynamics of Bacterial carpet using μPIV
- Static Obstacle Avoidance for Bacteria Powered Microrobots
- Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

V. Achievements

CONCLUSIONS

- ❑ Development of the obstacle avoidance algorithm for BPMs
  - Consideration of BPMs' characteristics and control systems design
  - Improvement of controllability for BPMs using electric fields
  - Robust approach for static and dynamic obstacle avoidance
- ❑ Validation through real experiments
  - Analysis of the motion of BPMs with the computed parameters
  - Comparison of performance with various environments
  - Evaluation of the potential risk using the danger index
- ❑ Quantification of the boundary effect
  - Visualization of the flow field on the bacterial carpet
  - Computation of the strength of the flow fields from tethered/untethered structures

CONTENTS

I. Introduction
- Motivation
- Reviews
- Objective

II. Research works
- Hydrodynamics of Bacterial carpet using μPIV
- Static Obstacle Avoidance for Bacteria Powered Microrobots
- Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

V. Achievements

Future works

1. **Adaptive parameters self-calibration for robust performance**
   - **Probability approach - Machine learning, Neural network algorithm**
   - **Increase of flexibility for environment**

2. **Swarming obstacle avoidance control**
   - **Swarm control of multiple microrobots**
   - **Centralized control**
   - **Improvement of accuracy locomotion**

CONTENTS

I. Introduction
- Motivation
- Reviews
- Objective

II. Research works
- Hydrodynamics of Bacterial carpet using μPIV
- Static Obstacle Avoidance for Bacteria Powered Microrobots
- Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

V. Achievements

Achievements

❑ Journal Publication

7. H. Kim, U K. Cheang, and M.J. Kim "Autonomous motion control for dynamic obstacle avoidance using Bacteria Powered Microrobots ", (preparing)
6. J. Ali, H. Kim, U K. Cheang, and M. J. Kim, "MicroPIV measurements of flows induced by rotating microparticles near a boundary", Physics of Fluids,2016 (pending)
5. U K. Cheang, H. Kim, M. Milutinovic, J. Choi, and M.J. Kim, "Feedback control of robotic achiral microswimmers," Journal of Bionic Engineering, 2016 (pending)
4. H. Kim, J. Ali, U K. Cheang, and M.J. Kim, "Micro manipulation using magnetic microrobots," Journal of Bionic Engineering, 2015, (pending)
3. H. Kim, U K. Cheang, D.H. Kim, and M.J. Kim, "Hydrodynamics of self-actuated bacteria carpet near boundary using microscale particle image velocimentry," Biomicrofluidics, 2015, 9, p. 024121.
2. H. Kim, M.J. Kim, "Electric Field Control of Bacteria-Powered Microrobots (BPMs) Using Static Obstacle Avoidance Algorithm," IEEE Trans. Rob., DOI (identifier) 10.1109/TRO.2015.2504370 .
1. H. Kim, J. Ali, K. Phuyal, S. Park, M.J. Kim, "Investigation of bacterial chemotaxis using a simple three-point microfluidic system". BioChip Journal, 2015, 9(1), 50-58

❑ Conference proceeding

5. H.Kim, U K. Cheang, and M.J.Kim, "Motion planning for particle based Microrobots for static obstacle avoidance", IEEE/RSJ IROS, 2016, Korea (pending)
4. J. Ali, H. Kim, Y. Liu, U K. Cheang, W. Sun, M.J. Kim, "Fabrication and magnetic control of alginate-based cellular microrobots," WBC. 2016.: Montreal, Canada.
3. U K. Cheang, H. Kim, D. Milutinovic, J. Choi, L. Rogowski, and M.J. Kim, "Feedback control of three-bead achiral microswimmers," URAI. 2015.: Goyang city, Korea. (Best Paper)
2. H. Kim, U K. Cheang, A.A. Julius, and M.J. Kim, "Dynamic obstacle avoidance for bacteria-powered microrobots," IEEE/RSJ IROS. 2015.: Hamburg, Germany.
1. H. Kim, U K. Cheang, and M.J. Kim, "Obstacle avoidance method for MicroBioRobots using electric field control," IEEE-CYBER. 2013.: Hong Kong, China (Final list for best paper)

Acknowledgements

I sincerely thank

- The committee members
  - Prof. Ajmal Yousuff
  - Prof. Young Cho
  - Prof. Bor-Chin Chang
  - Prof. Allon Guez
  - Prof. Min Jun Kim
- Current and past labmates
  - Dr. U Kei Cheang, Jamel Ali, Armin Darvish, Dr. Paul Kim, Dr. Gaurav Goyal, Dharma T. Varapula, Rafael Mulero, Dr. Anmiv Prabhu, Dr. Kevin Freedman, Dr. Dalhyung Kim. Dr. Wonjin Jo.
- Our collaborators
  - Dr. Agung Julius
- Colleagues
  - Dr. Qudus, Yoontae Kim, Dr. Jessica Snyder, Dr. Reyhan Taspinar, Chengyang Wang, Bin Lei, Yigong Liu, Luffi Agartan, Dong-Ook Kim and Hyunjoo Oh.
- All of the attendees

Q & A